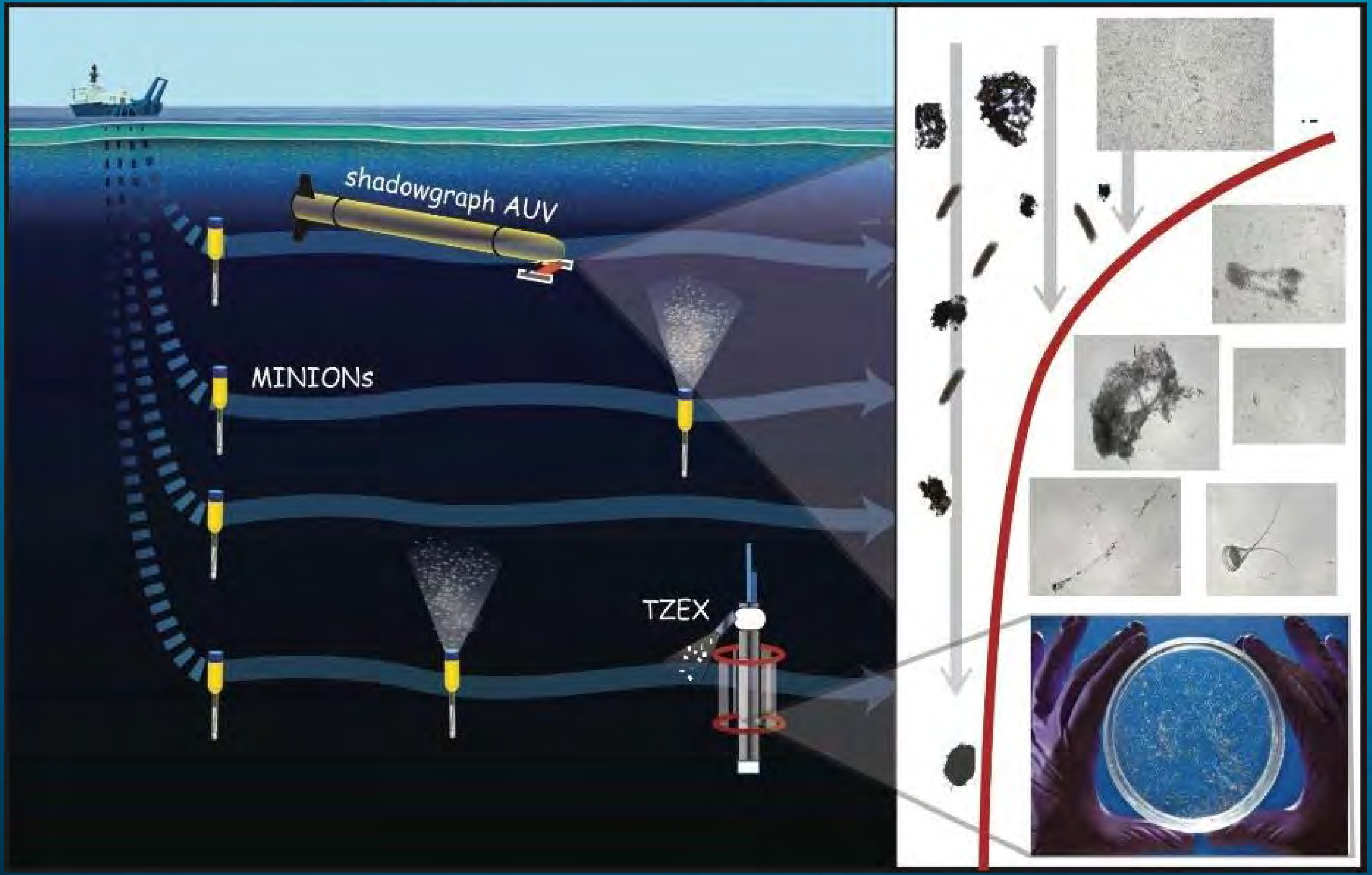
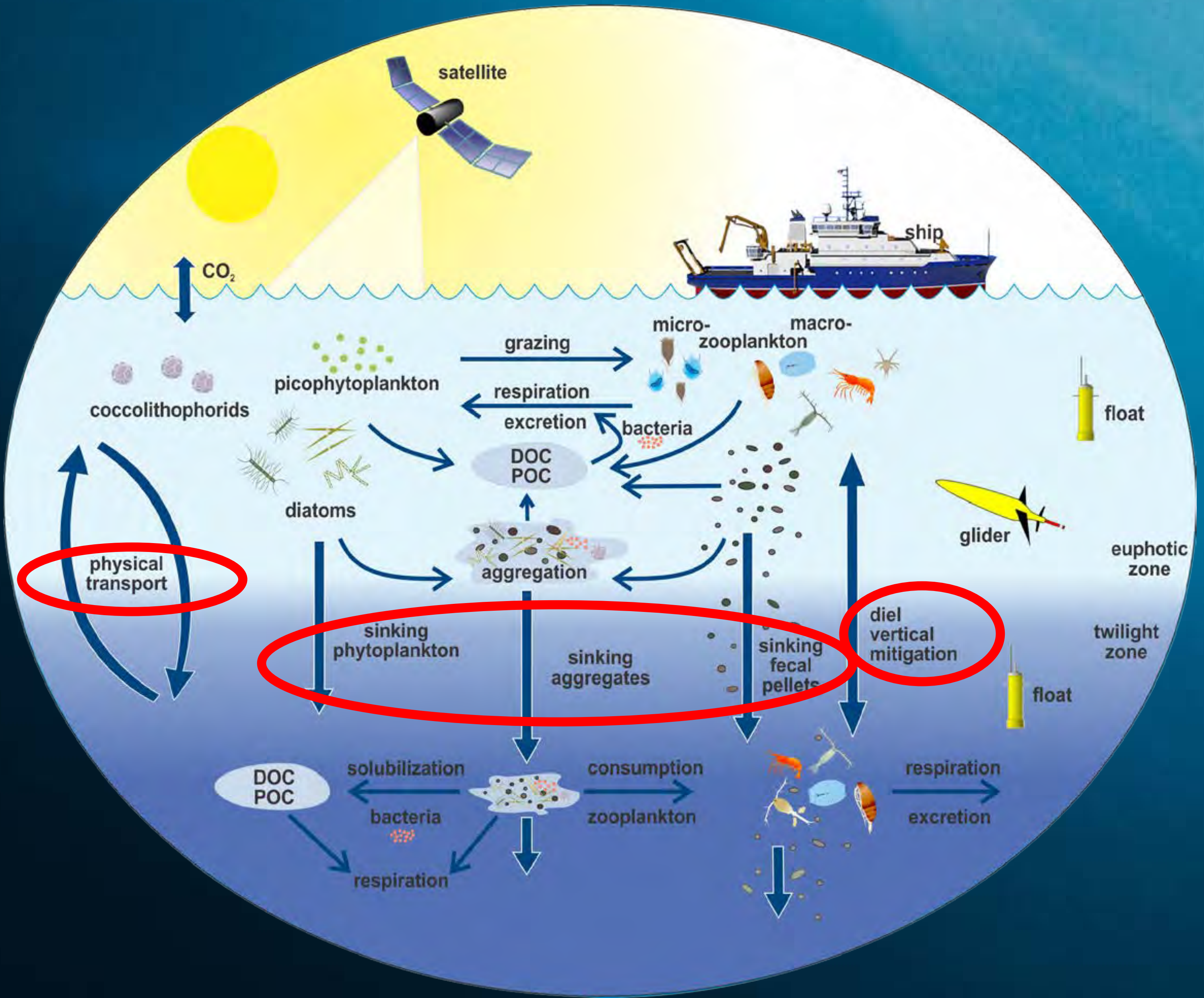
New technologies for MRV of ocean CDR associated with the biological C pump- examples (mostly) from EXPORTS and OTZ

Ken Buesseler, with help from:
D. Siegel, H. Sosik M. Estapa,
C. Durkin, M. Omand
and E. Ceballos-Romero



WOODS HOLE
OCEANOGRAPHIC
INSTITUTION

Biological Carbon Pump



Combined processes that remove CO_2 from the atmosphere and transport C to the deep sea

5-12 Gt C/yr leaving sun lit surface
1-2 Gt C/yr reaches 1000 m

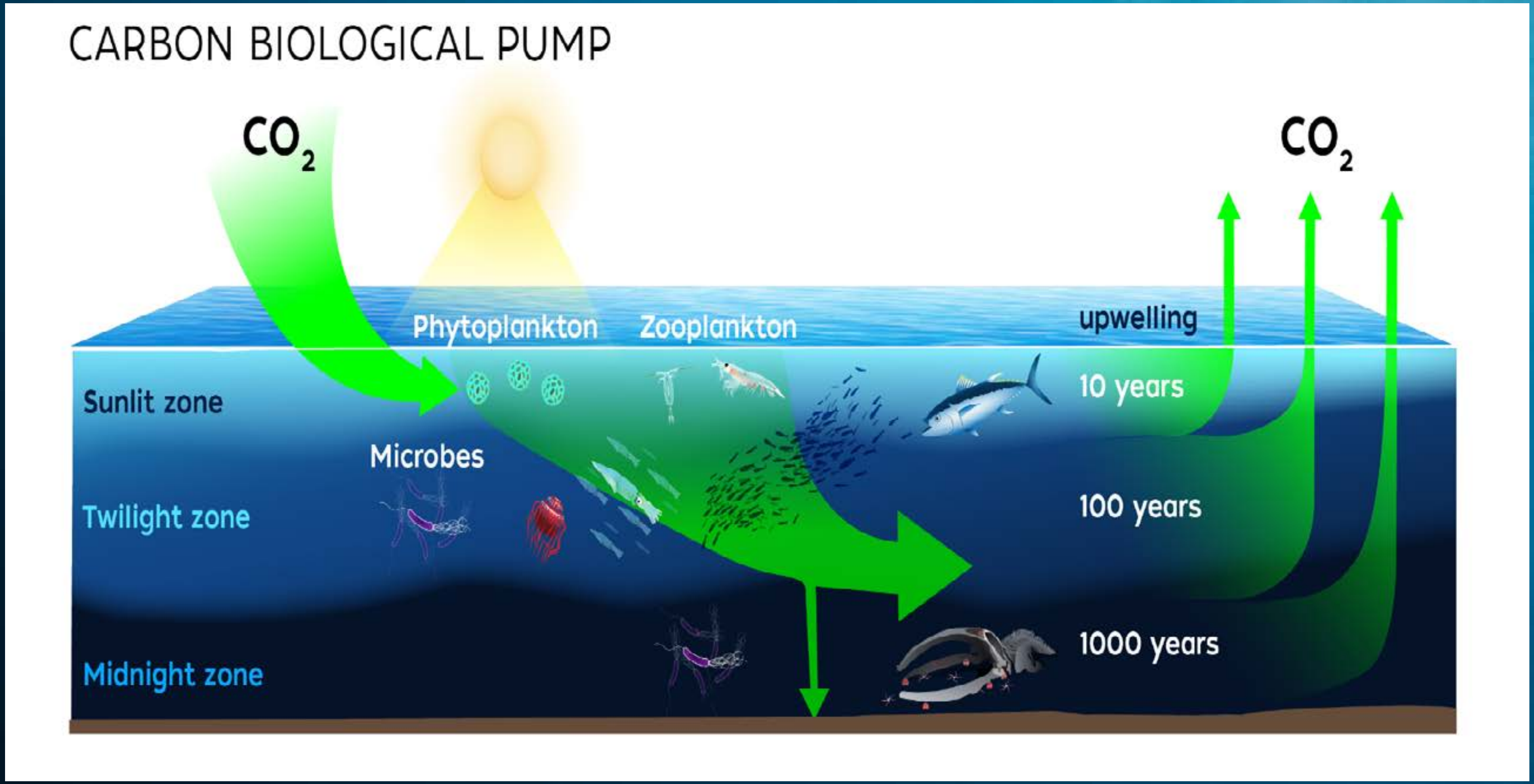
BCP sets dissolved inorganic C (DIC) gradients- impacts solubility pump

Remove BCP and atmos. CO_2 increases 200 ppm

Change depth of remin. by 25 m and atmospheric CO_2 decreases by 10-30 ppm

BCP- Variable magnitude, changes with depth, hard to quantify precisely

Biologican C pump MRV for ocean CDR
- mostly relevant for upwelling tubes, ocean fertilization and seaweed CDR approaches

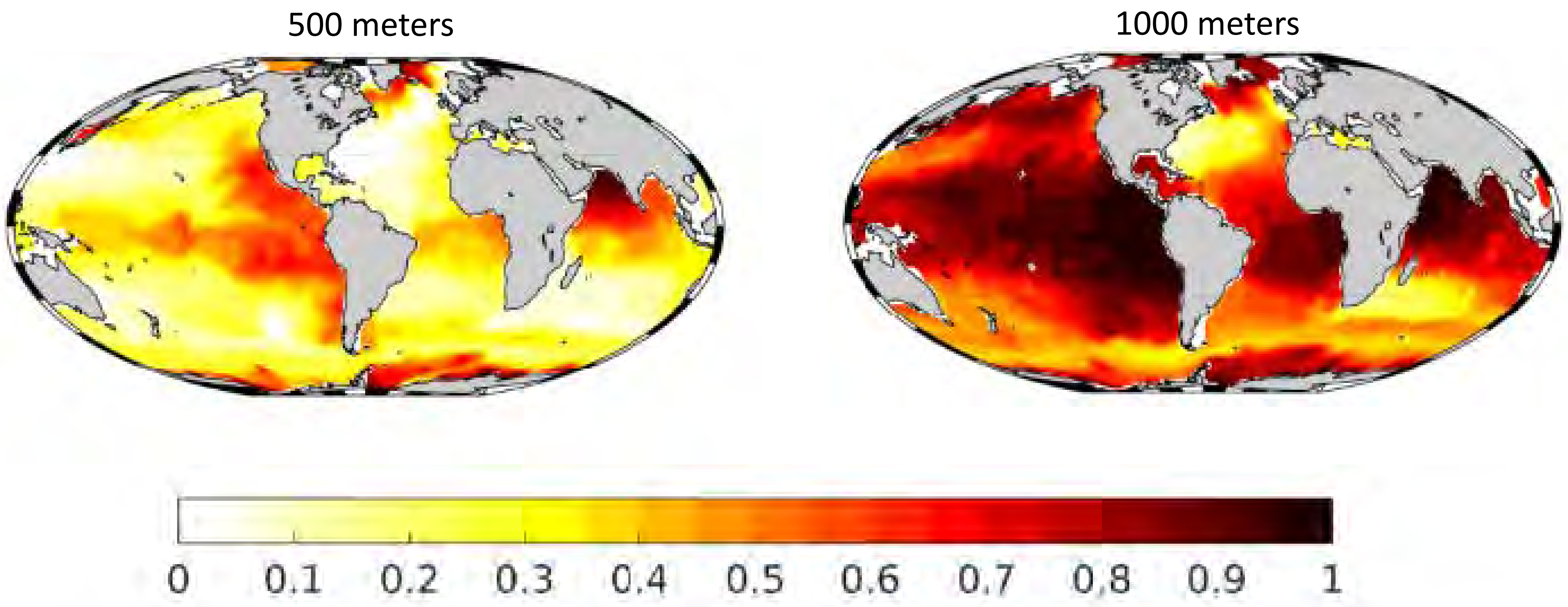


Durability depends upon how deep C is removed in the ocean

Diel migrations and most of the physical C “injection” pumps impact upper 1000m

To get deep enough for sequestration time scales >100 yr, mostly concerned with gravitational sinking

Ocean can only store carbon durably if it gets deep enough and in the right locations (& how would we know?)



Fraction of carbon stored for greater than 100 yrs

From Siegel et al., 2021

How do we measure the strength and efficiency of the biological C pump?

Direct collection of sinking particles

- Sediment traps since 1970's.
- Issues wrt collection efficiencies, swimmers and preservation
- Ultimately limited coverage for MRV in space/time, if samples need to be returned

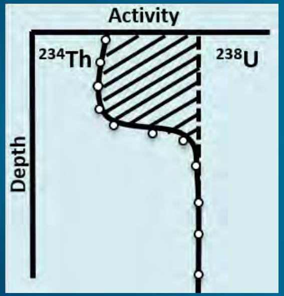
Imaging/optics

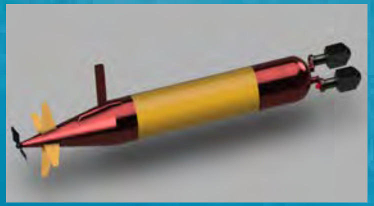
- Count/image particle #'s and size- convert to C flux with sinking rate and C content
- Count/image particles as they sink vertically

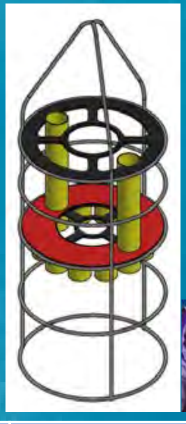
Stocks/mass balances

- Geochemical mass balances-
  - C (dissolved and particulate forms), and/or nutrients
  - O_2 (linked to production and remineralization)
  - Stocks are huge relative to fluxes making closing budgets difficult
- Natural radionuclides-
  - provide "clocks" to quantify rates of particle removal
  - physical usually small relative to radioactive disequilibrium terms in models

Examples of approaches suitable for MRV of ocean CDR

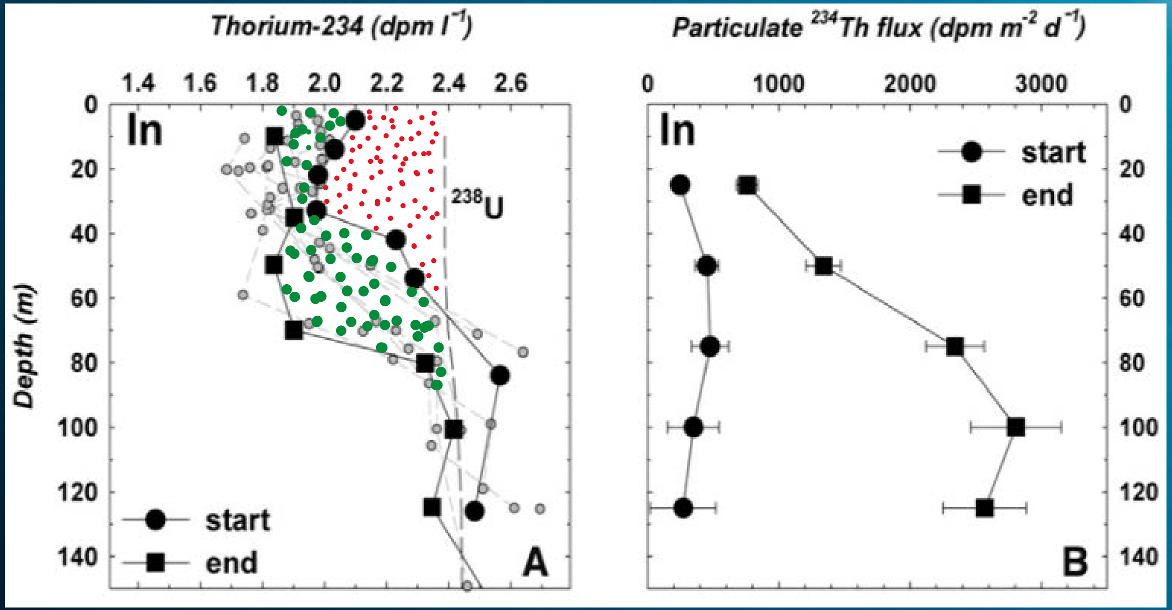


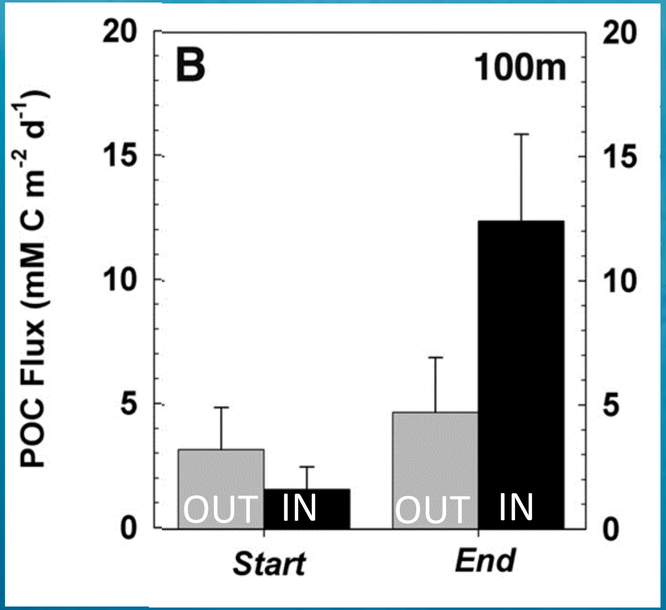




	Thorium-234	UVP camera	Optical Sed trap	Shadowgraph camera	MINIONS	TZEX trap and gels
How	Less Th = higher CDR	Plankton & detrital images/ID	Optical light attenuance = C flux	Plankton & detrital images/ID	Detrital C flux & ID	Samples for calibrations and ID
t-scale	Days-weeks	Minutes-weeks	Hours-days	Minutes-days	Minutes-weeks	Days-weeks
Depths	0-500m	0-6000 m	0-2000 m	0-1000+m	0-500+ m	0-1000+m
Size Range	C/Th on >50 um	>60-100 um – 1 cm	Non-imaging flux sensor	50 um – 10 cm	1 mm – 1 cm	10 um – 10 cm
Area/volume	SMS scales (km)	0.7-1.1 L	10's km2 source funnel	Several L/frame; 20/sec	10's km2 source funnel	10's km2 source funnel
TRL	In-situ low	High	Med	Med	Low/med	Low/med
Cost/inst	<$10K	$27-50K	V1: $15K? V2: ?	>$50K	<$5K	$100K
Platform	Surface float & AUVs	CTD, moorings, profiling floats	Profiling floats &?	Towed and LRAUV	Lagr float	Profiling float
Markets	**	**	**	*	**	*

US SOFeX results- just add iron!
How did we quantify C loss out of surface?





Radionuclides profiles provide quantitative rates of C removal via sinking particles

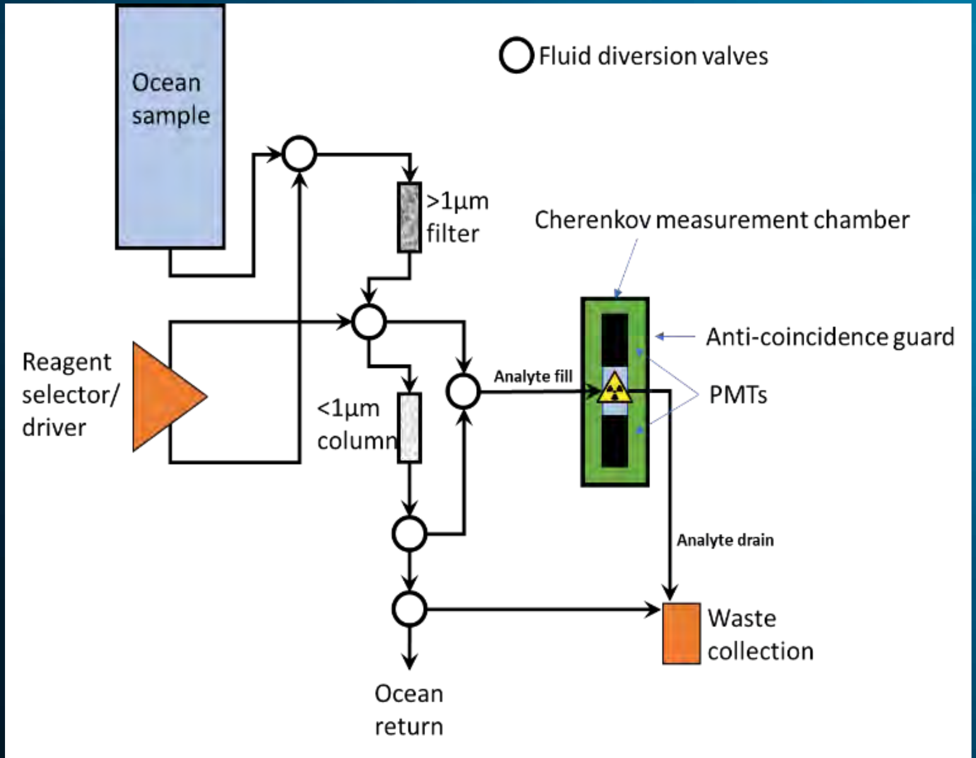
C flux = Th flux x C/Th

Low thorium-234 = high flux

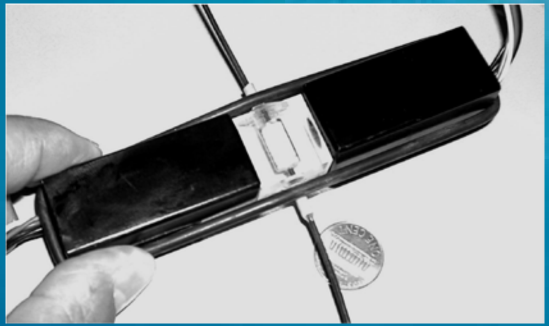
At start of SOFeX, flux of sinking particles out of upper 60 m only
With Fe & 28 days, flux increases and deeper

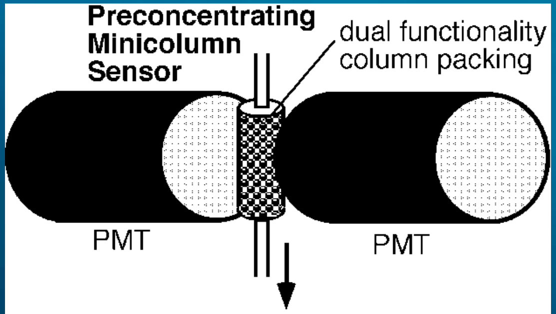
Expt. to look at Fe impacts on surface ecosystems
1.3 tons Fe added
80 µatm drawdown CO_2
2100 tons C below 100m
CDR MRV the hard way!

What if we could collect and measure thorium-234 in-situ?



On board collection-
- water or direct on columns (several L's)



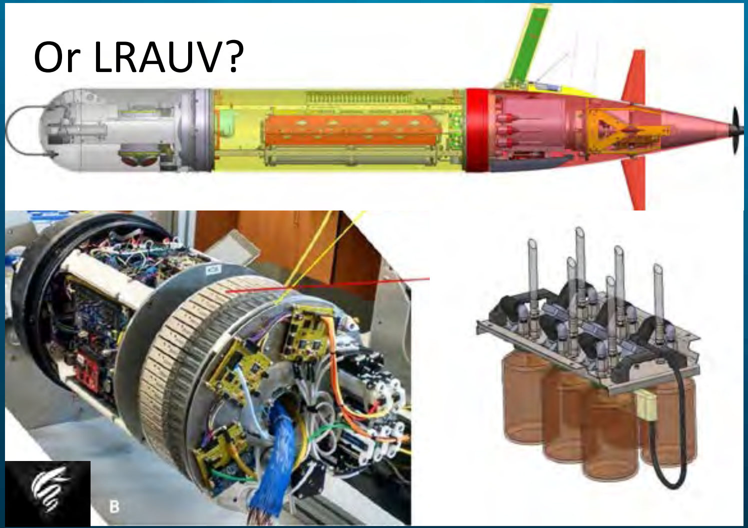


Mini-sensors measure light
-scintillating beads or
Cerenkov detection
(high energy beta's)

Surface AV, buoy

^{234}Th detector, pump & other sensors- Flu, pCO_2, etc.

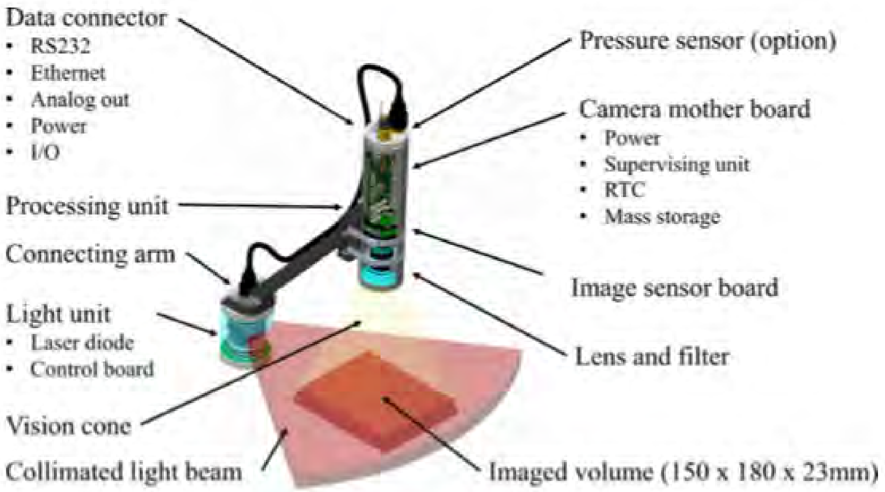
Subsurface collection ports



Buesseler, Benitez-Nelson, O'Hara, Grate- RFI

Underwater Vision Profiler - UVP

- Images particles from 100 µm to 2.6 cm providing 4 Hz
- Can be deployed from CTD & on autonomous platforms
- Sample volume ~0.7 L (UVP6)
- Vignettes saved for off-line analyses for classifying large objects (> 0.6 mm)
- Data flows through EcoTaxa website

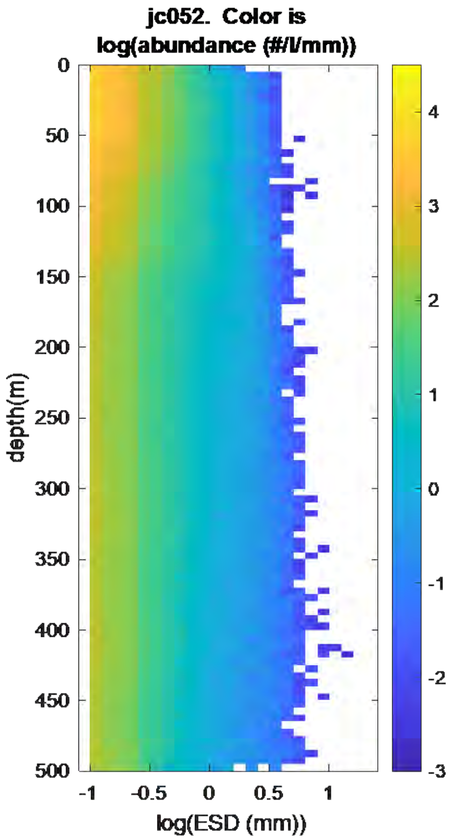


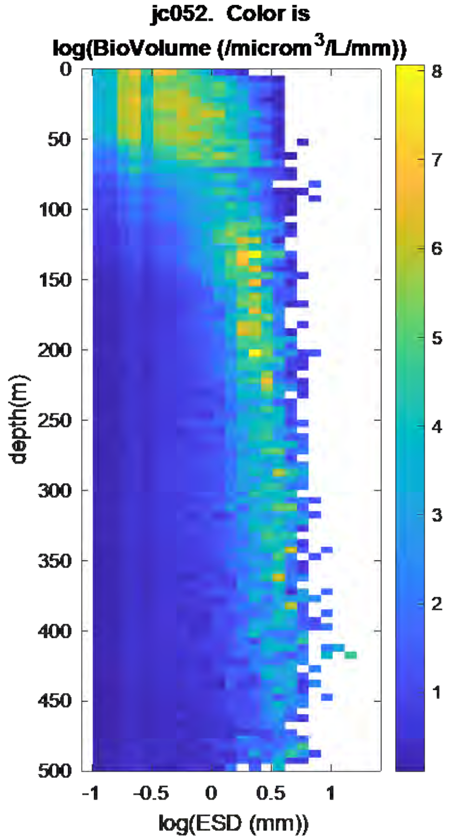
UVP-6
Picheral et al. (2021)

EXPORTS N. Atlantic- Siegel et al.

Particle Abundance (#/L/mm)

Biovolume (ppmv/mm)





large

UVP-5 In Action During EXPORTS…

- EXPORTS sampled the demise of the North Atlantic Spring Bloom in May 2021
- Observations started as a diatom bloom ended within a retentive eddy feature
- White spaces are weather days
- Data from UVP's on 3 ships on CTD/Rosette

May date

Siegel et al.

Sinking POC Flux from aggregate PSD

In theory…

$$POC = \int_{D_{min}}^{D_{max}} N(D)\, \rho_C(D)\, w_s(D)\, dD$$

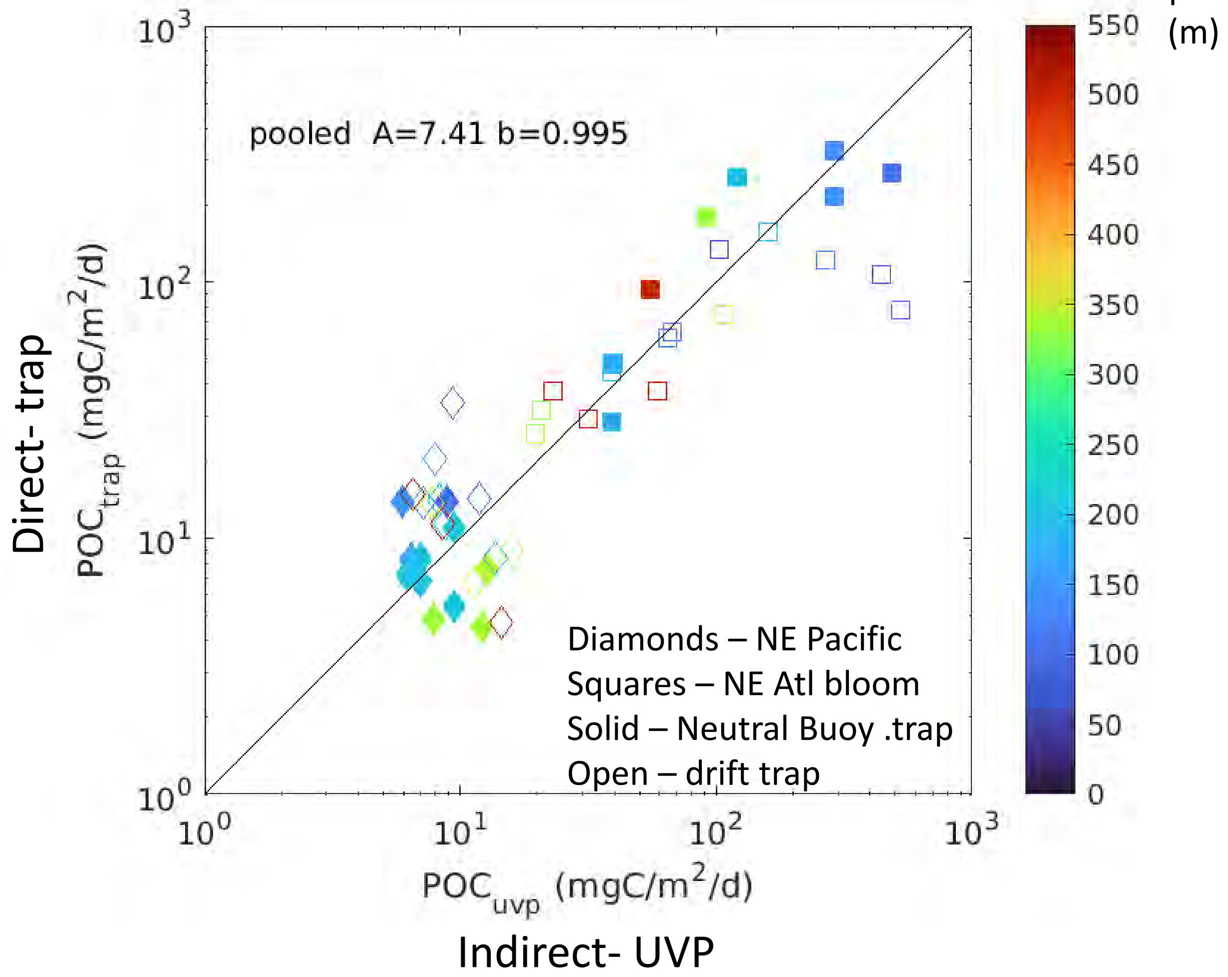
need PSD, **carbon content & sinking speed**

In practice…

$$POC_{uvp} = \int_{D_{min}}^{D_{max}} N(D)\, A\, D^b\, dD$$

assume power law for carbon content & sinking speed and **fit the A & b coefficients** (Guidi et al. 2008)

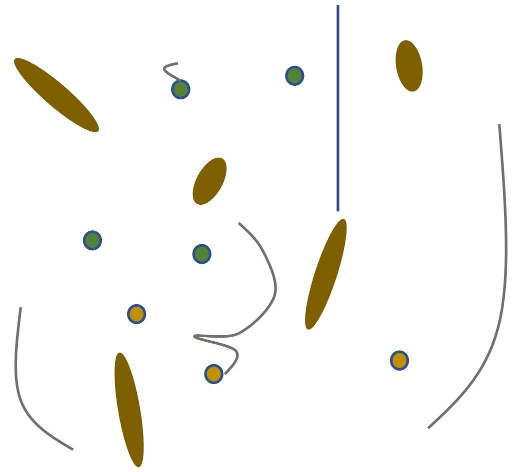
Fits are OK on global scales – but large uncertainties remain on local / regional scales



Next Steps: Improved particle ID; larger sampling volume to see larger particles; higher resolution for smaller particle sizes; fluorescence illumination to discriminate pigmented particles; calibration….

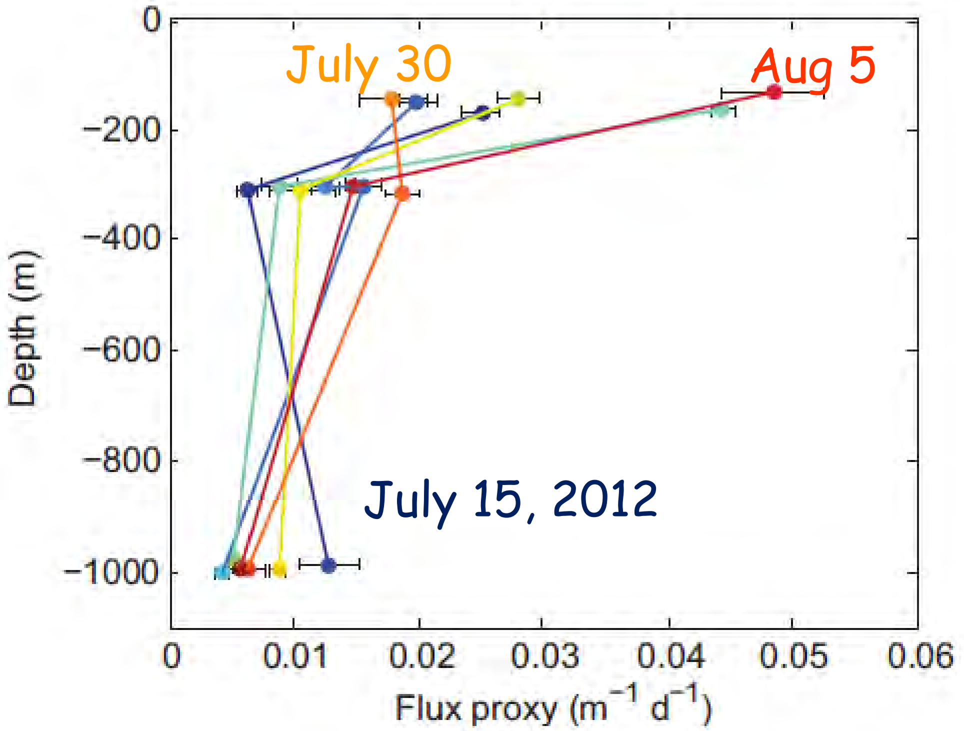
Optical Sediment Trap (OST)

Physical interception and optical detection of sinking particles
Direct flux measurement = no need to assume particle sinking speed
Carbon content must be inferred from light attenuation or images



“OST V1” = transmissometer

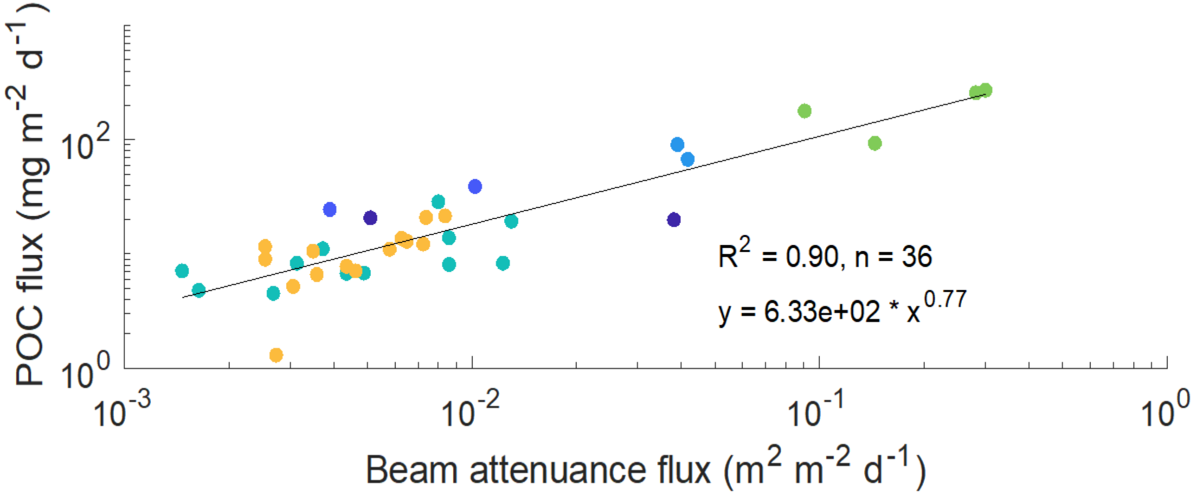
OST at BATS



OST signal of <u>sinking particles</u> over 18-24 hr at BATS- *Estapa et al. 2013*

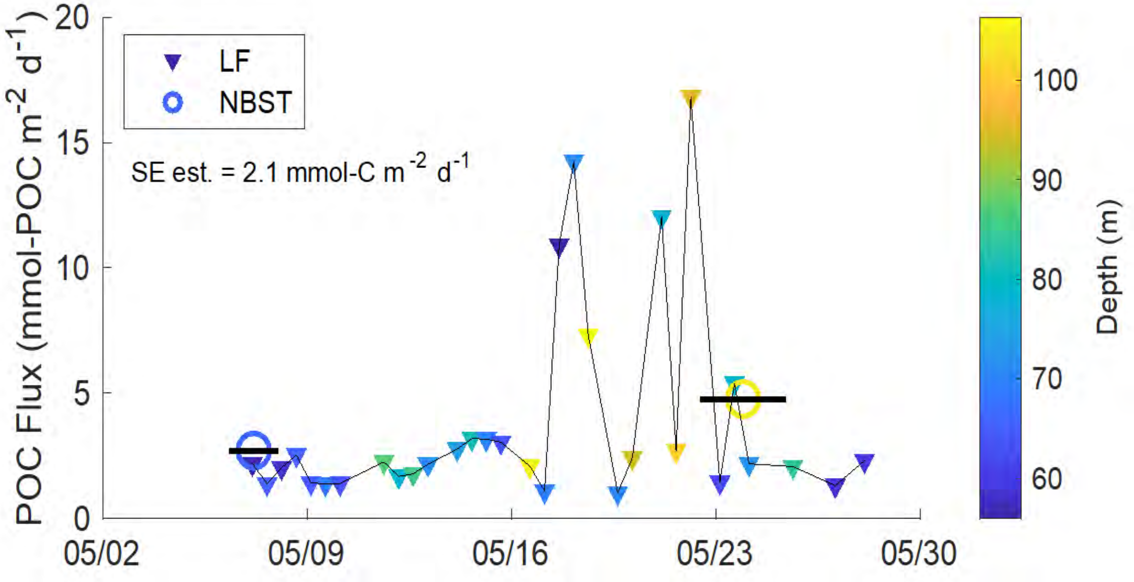
Estapa et al., Bishop et al.

Beam attenuance flux and POC flux are strongly related



Data compilation from published and unpublished sources: Estapa (UMaine), Durkin (MBARI), Omand (URI), Buesseler (WHOI), Baker (NOC).

Onset of high flux from North Atlantic bloom during EXPORTS starts on May 17th



Data example from EXPORTS (Estapa (UMaine), D'Asaro (UW/APL), Omand (URI), preliminary/unpublished)

Next steps:

"OST V2" development (Sequoia Scientific, Inc. and UMaine, with NSF-STTR support):

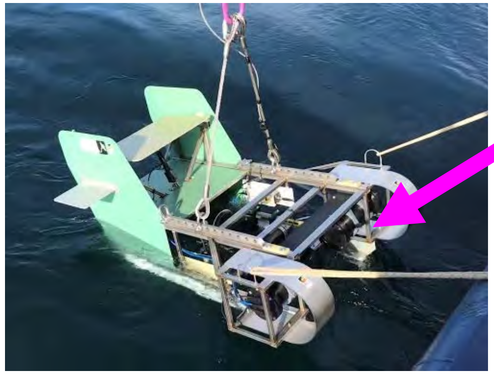
- Simple, non-imaging, quantitative POC flux sensor
- Designed for easy addition to distributed network of drifting platforms (e.g. BGC-Argo) or complement to imagers (e.g. MINIONS)

Improvements:

- Non-shading housing design
- Larger particle collection area
- Lower cost (target = $10K once in commercial production)

"OST V2" concept

Estapa et al.



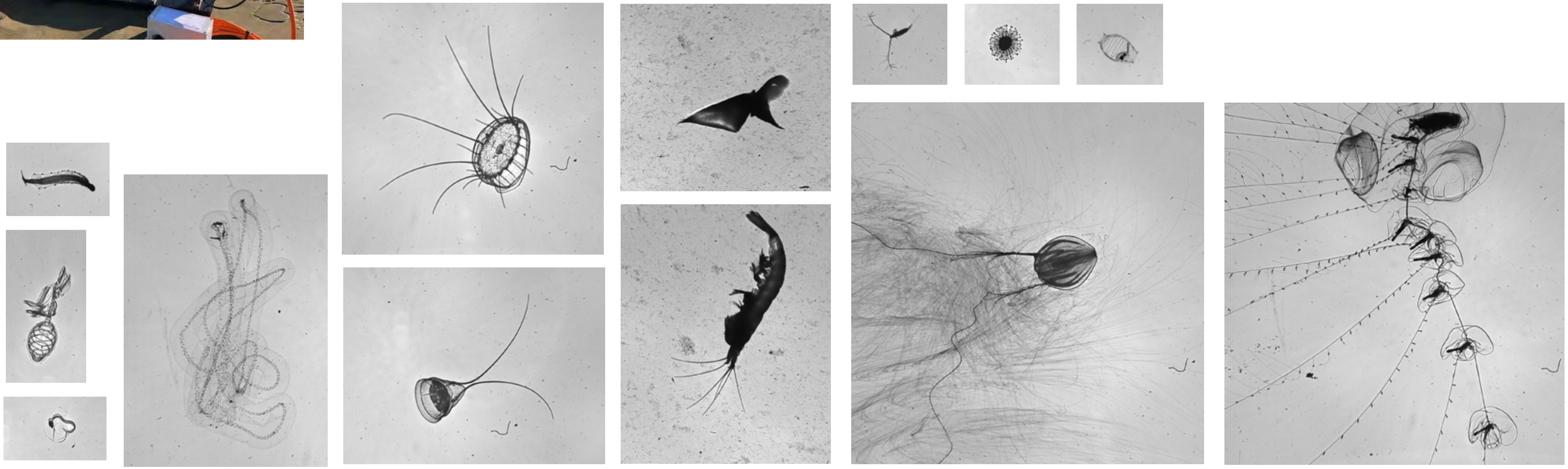
Shadowgraph imager

Sosik et al. lead
Deployed on towed sled in N. Atlantic EXPORTS

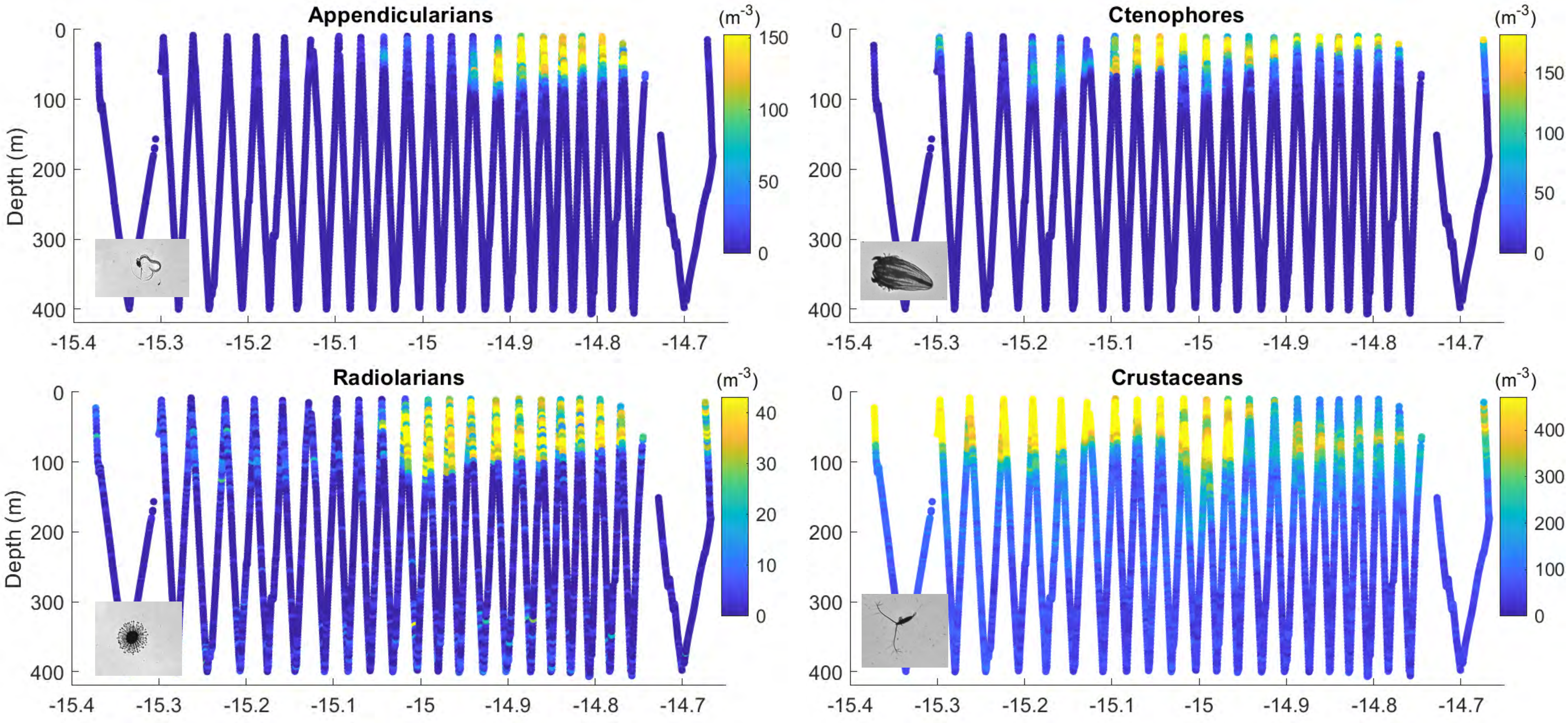
OCEAN TWILIGHT ZONE

~8 x 10 cm camera field, 30 cm depth
2.3 L per frame, 15 frames s^{-1}

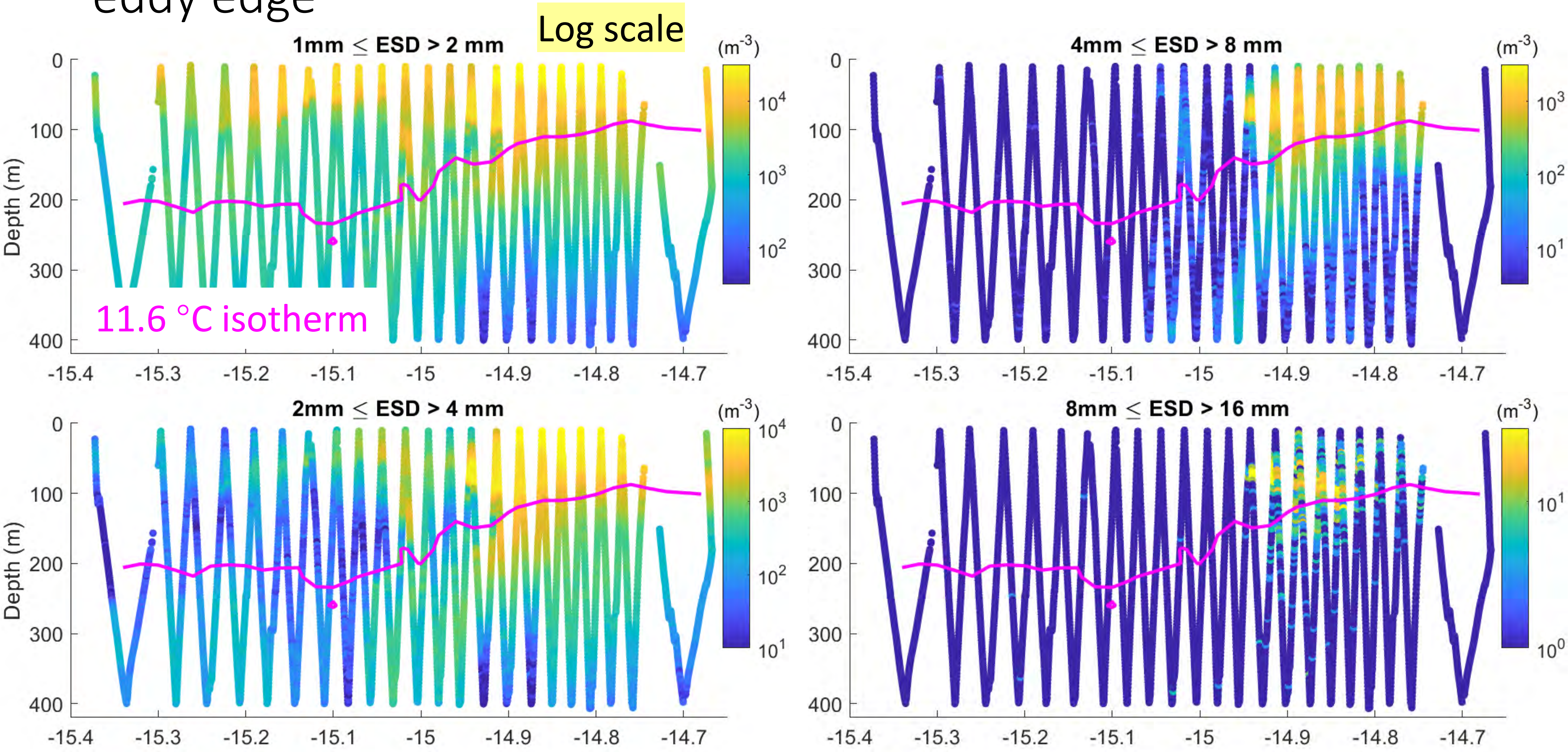
Automated processing for target detection- 10,374,677 extracted ROIs
Supervised machine learning classification- 29-category classifier applied to ROIs



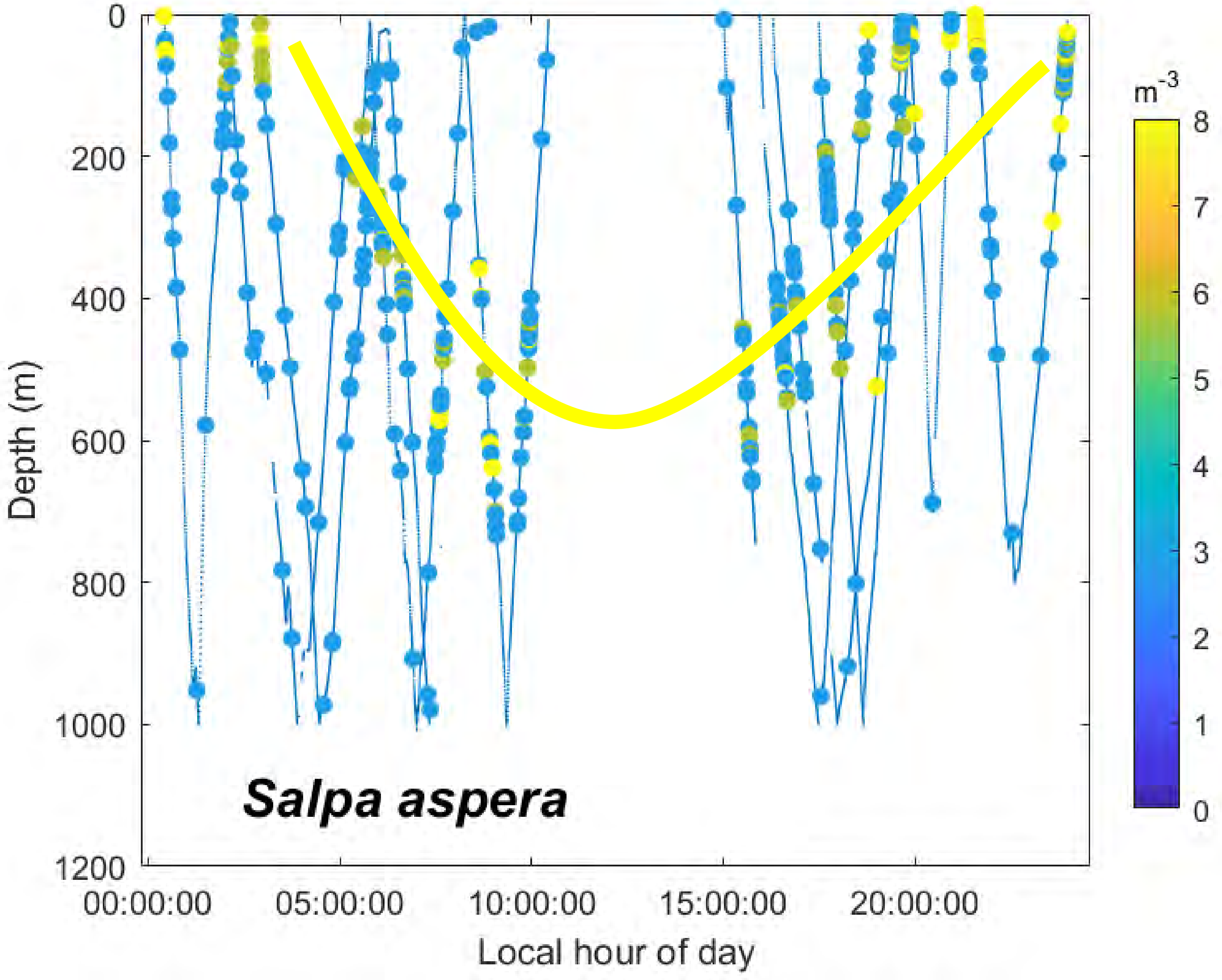
Abundant zooplankton groups occupy different water masses across the eddy edge

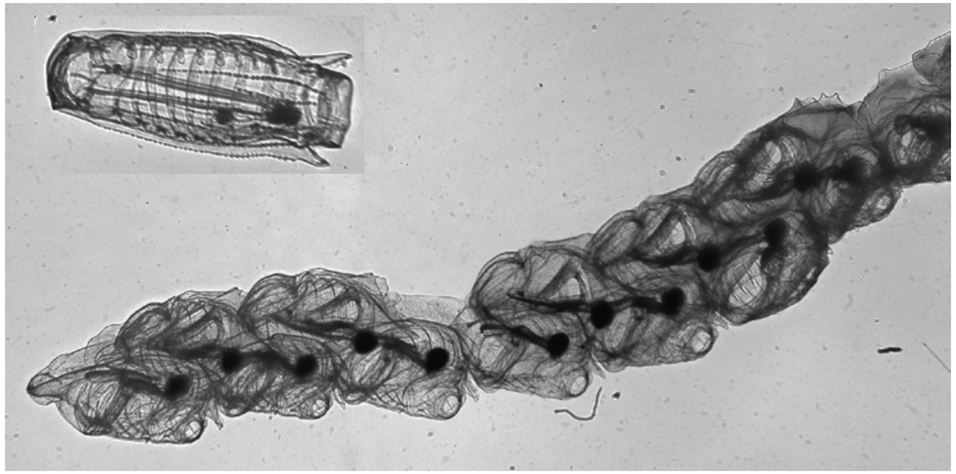


Marine snow size classes are spatially structured across the eddy edge

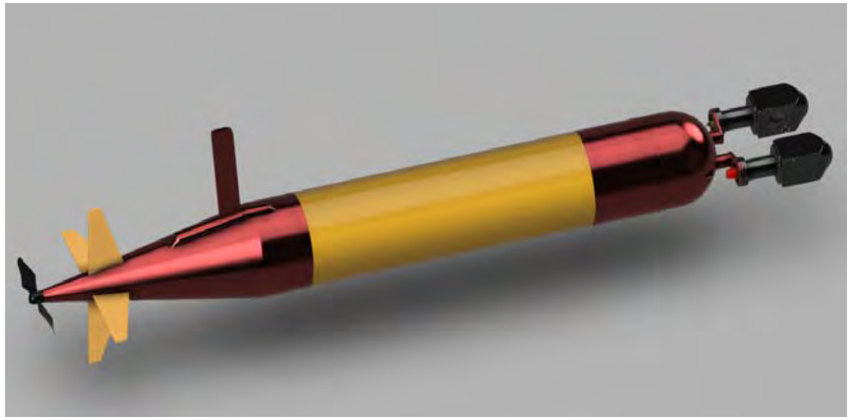


Time-resolved imaging can quantify taxon-specific diel vertical migration

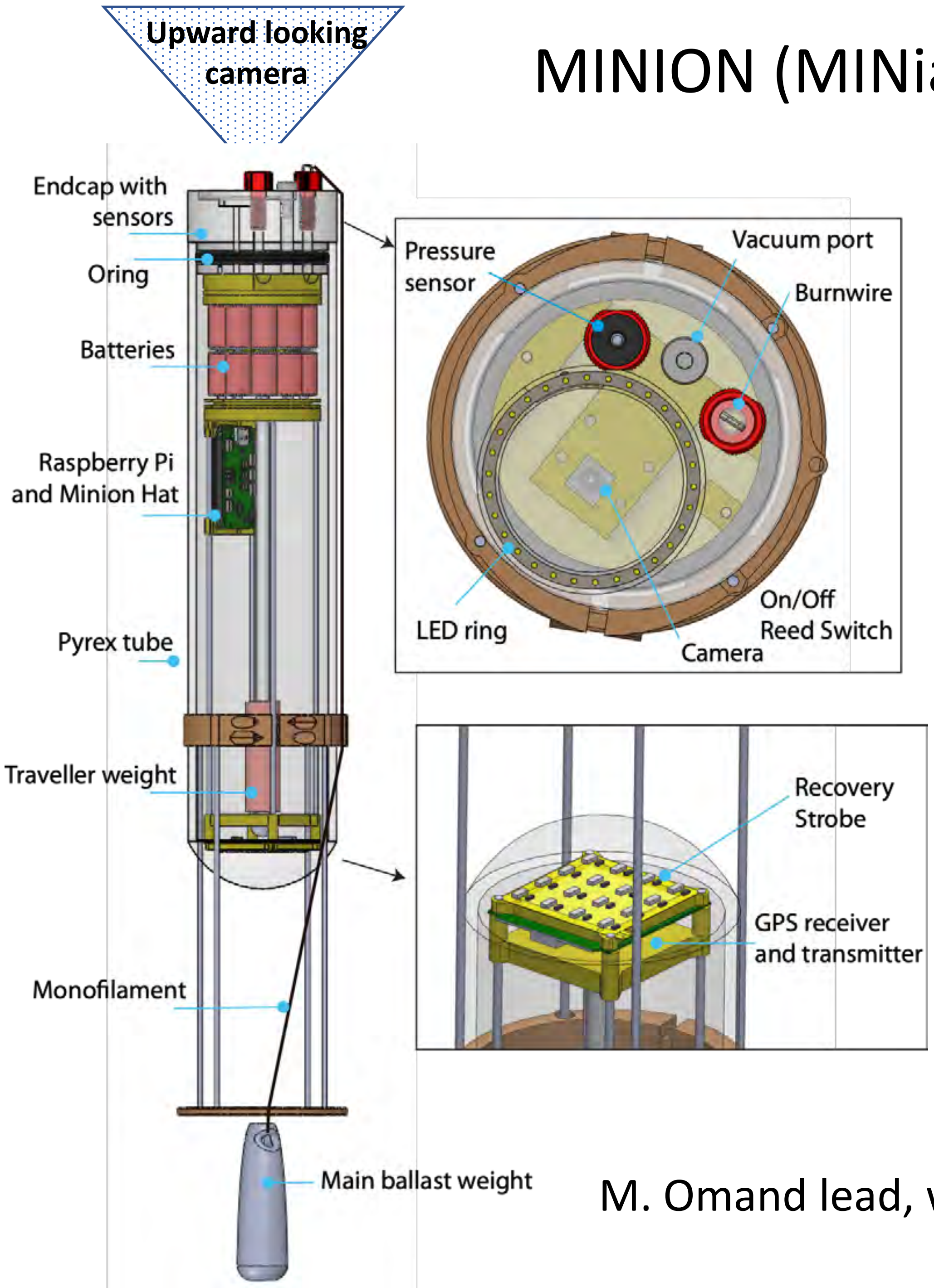


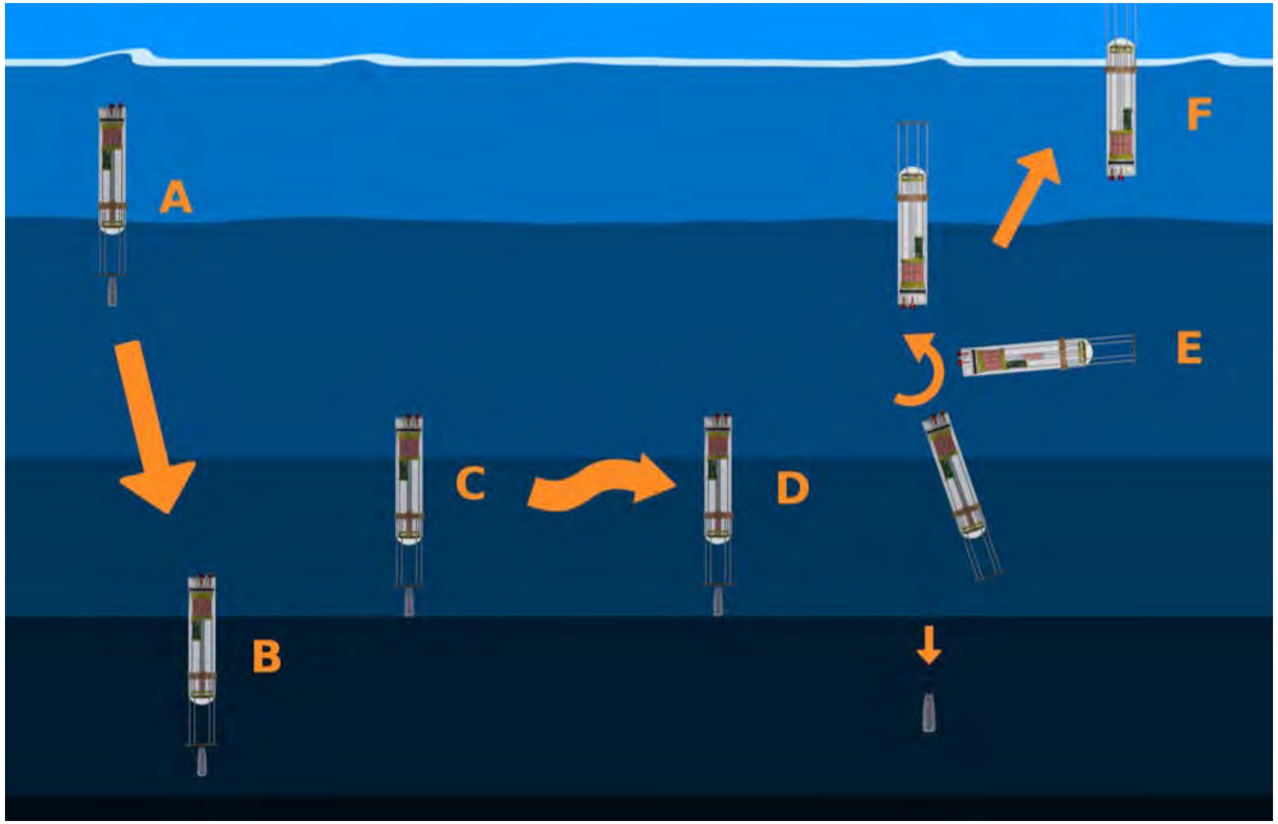


Next steps:
LRAUV platform



MINION (MINiature IsOpycNal) floats

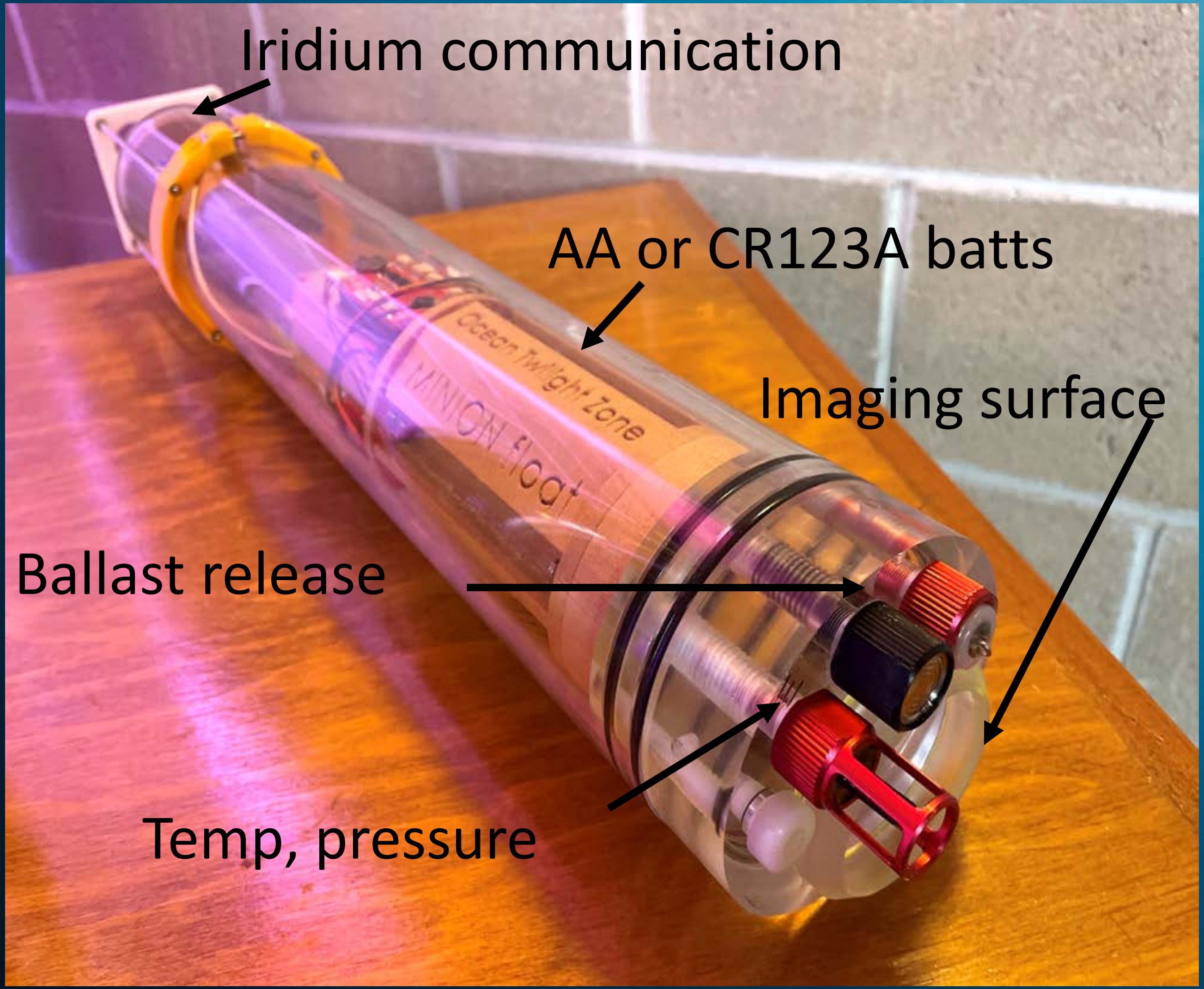




Deploy days-weeks, currently upper 500 m
Goal- deploy "swarms" for multiple depth 4D sampling

M. Omand lead, w/ collab. at WHOI, MBARI, MIT, NASA

Upward looking camera with gel trap example- Omand



Next steps:

Added capabilities
- fish tags (track in situ currents)
- O_2 sensor
- horizontal camera for sinking rates

On board image processing & data transmission

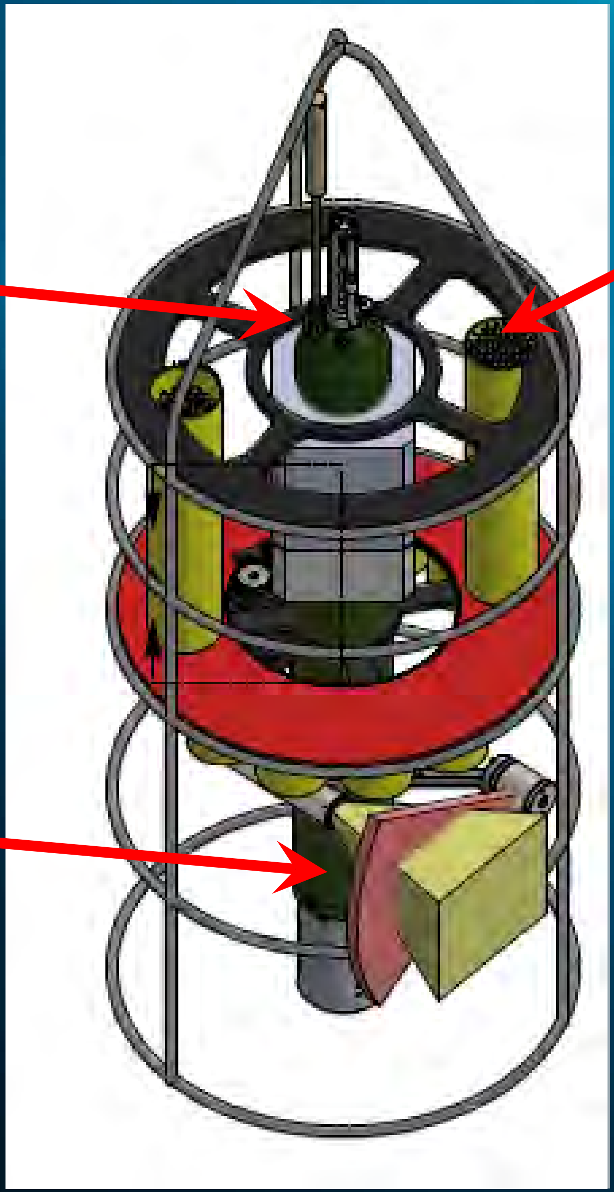
Mass production- parts <$1-2K

Calibrate C flux estimates from images with other devices (TZEX)

Twilight Zone EXplorer (TZEX) - "ocean truthing" essential for MRV

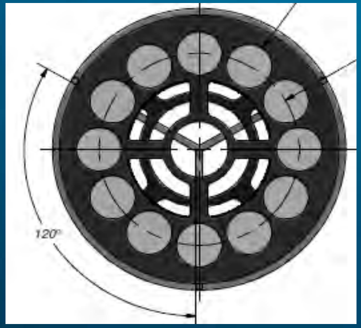
Profiling float- NKE w/ sensors

UVP 6 Horz. mount for sinking speeds



Two sampling tubes for sinking particles

12 position sampling carousel McLane Indust.



Deploy to park depth for collection - hours (D/N) to days/weeks

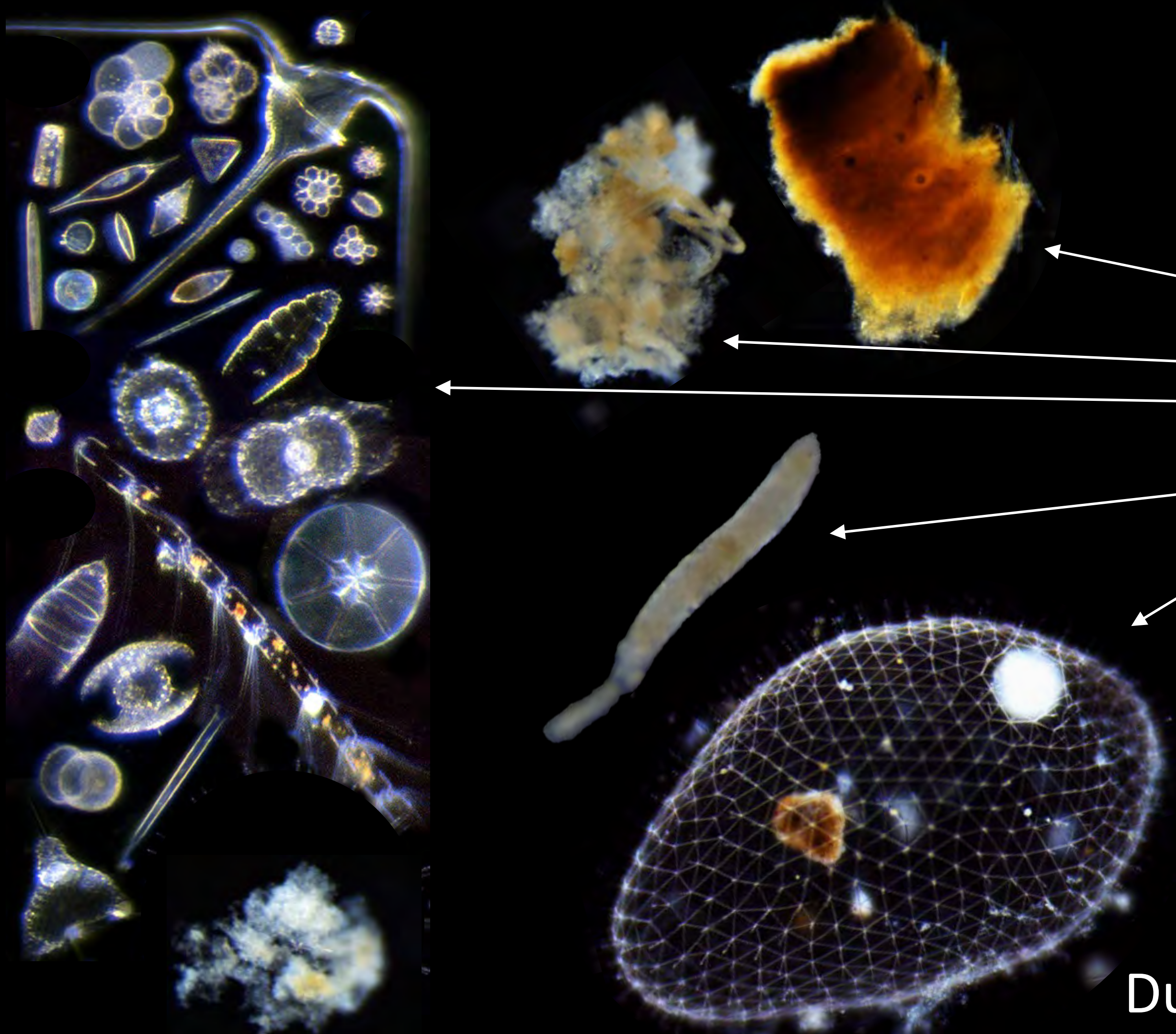
Profiling upper 1000 m w/std sensors and UVP

Flux collections
- key to calibrations
- preserved for geochemical, microbial analyses

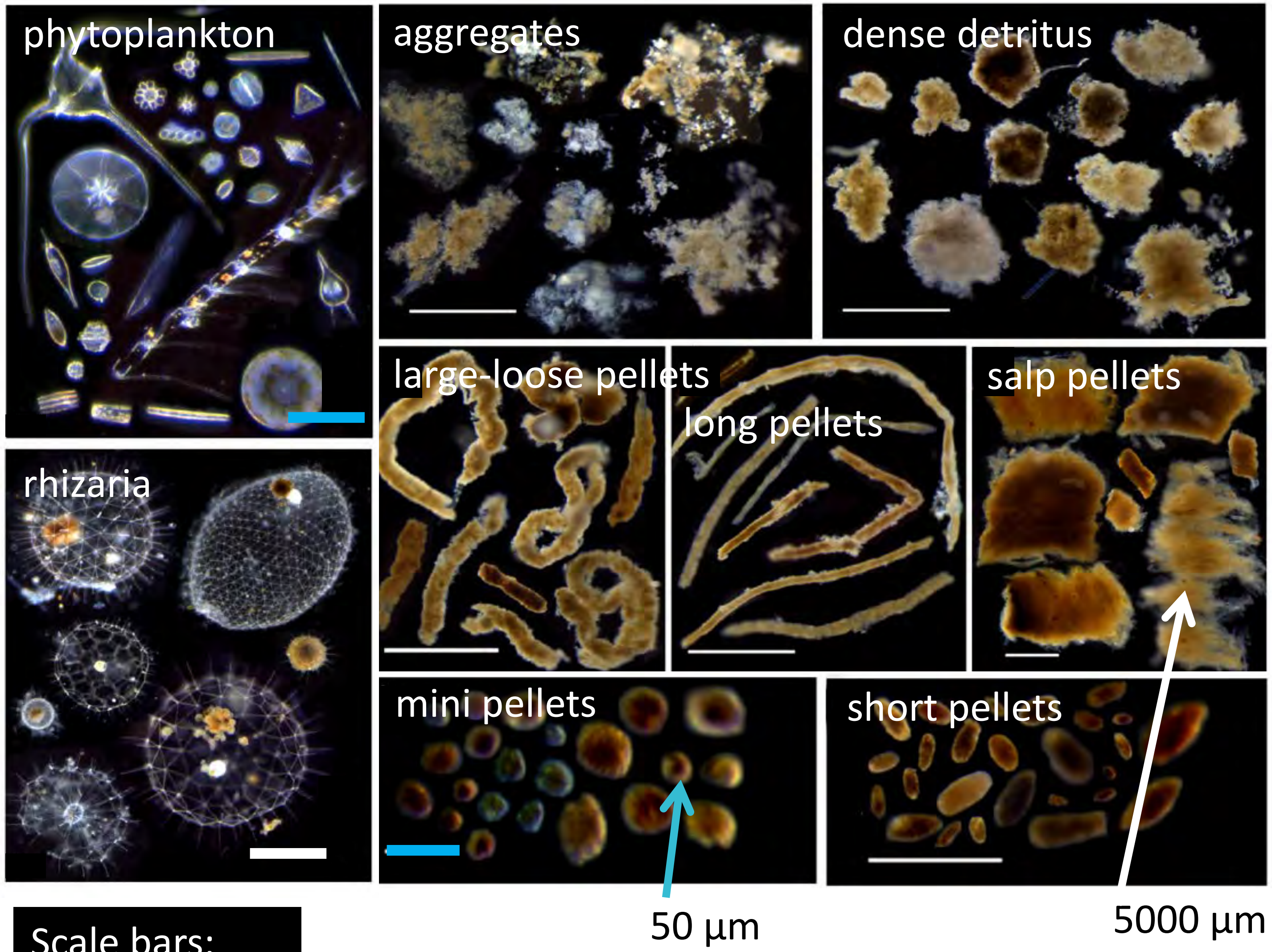
Polyacrylamide "gel" collections

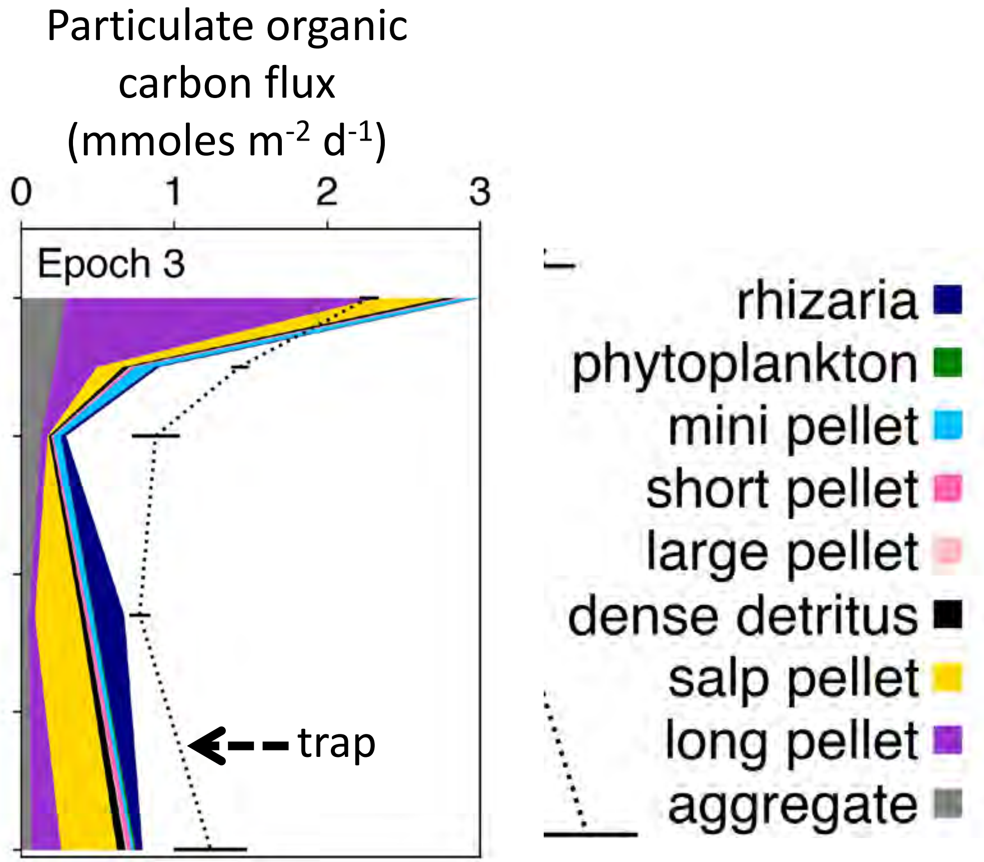
K. Tradd, K. Buesseler, E. Ceballos-Romero, NKE, McLane

Gel traps- PSD & ID characterization of what is sinking



Durkin et al.





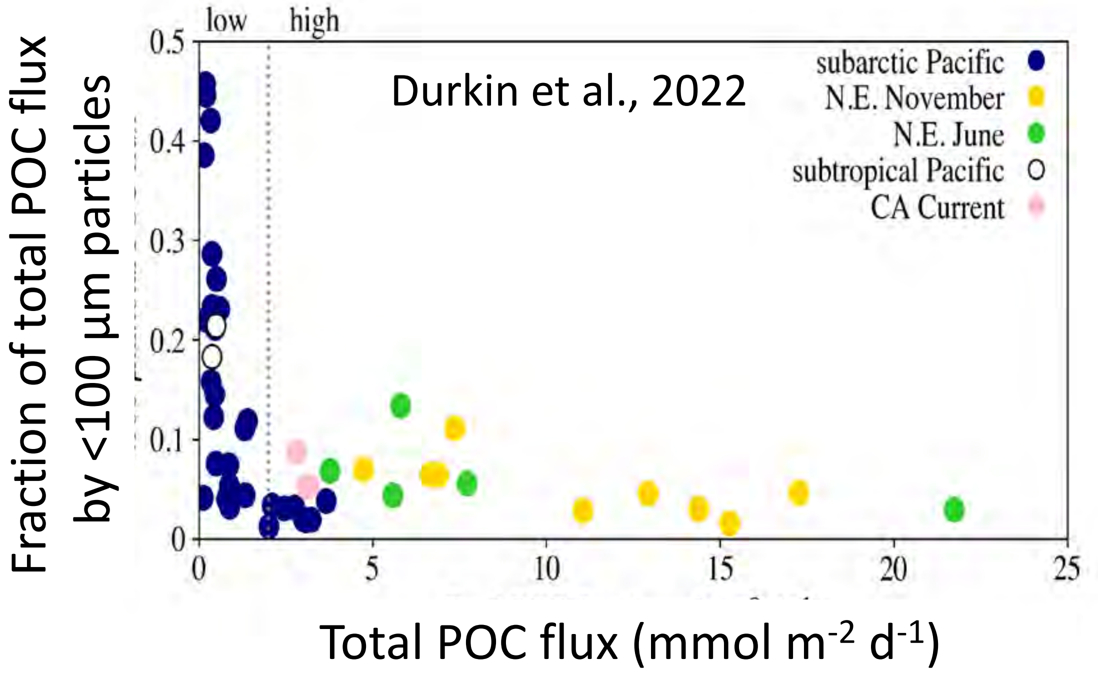
Scale bars:
White = mm
Blue = 100 µm

Durkin et al.

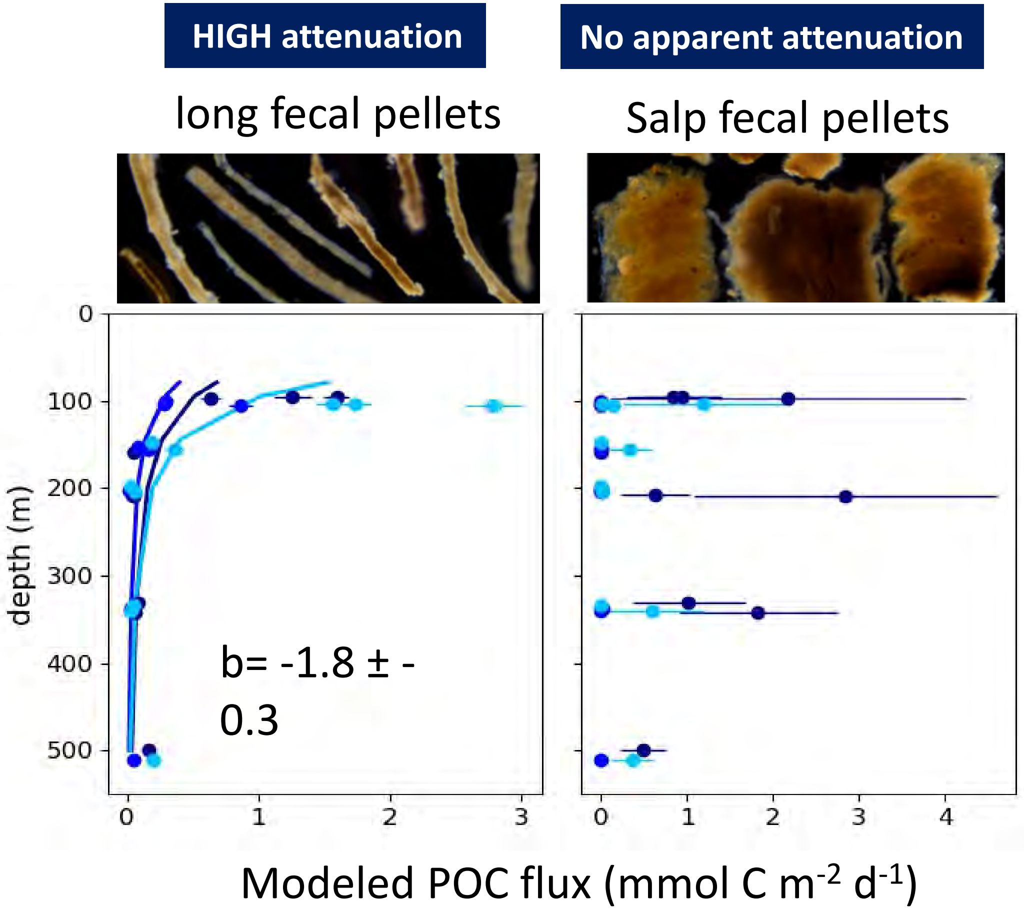
What size particles contribute most to C flux?

Small particles (<100 µm) were consistently ~5% of total POC flux

Small particles export relatively more POC in low flux environments

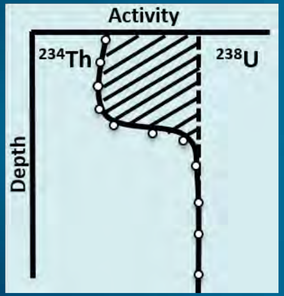


How does attenuation differ between particle types?

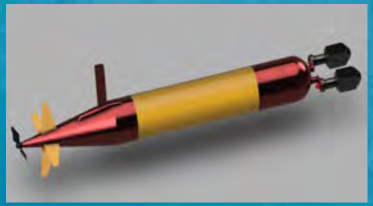


Next steps: co-deployment TZEX w/ MINIONS & other sensors/imagers for C flux intercal

Examples of approaches suitable for MRV of ocean CDR







	Thorium-234	UVP camera	Optical Sed trap	Shadowgraph camera	MINIONS	TZEX trap and gels
How	Less Th = higher CDR	Plankton & detrital images/ID	Optical light attenuance = C flux	Plankton & detrital images/ID	Detrital C flux & ID	Samples for calibrations and ID
t-scale	Days-weeks	Minutes-weeks	Hours-days	Minutes-days	Minutes-weeks	Days-weeks
Depths	0-500m	0-6000 m	0-2000 m	0-1000+m	0-500+ m	0-1000+m
Size Range	C/Th on >50 um	>60-100 um – 1 cm	Non-imaging flux sensor	50 um – 10 cm	1 mm – 1 cm	10 um – 10 cm
Area/volume	SMS scales (km)	0.7-1.1 L	10's km2 source funnel	Several L/frame; 20/sec	10's km2 source funnel	10's km2 source funnel
TRL	In-situ low	High	Med	Med	Low/med	Low/med
Cost/inst	<$10K	$27-50K	V1: $15K? V2: ?	>$50K	<$5K	$100K
Platform	Surface float & AUVs	CTD, moorings, profiling floats	Profiling floats &?	Towed and LRAUV	Lagr float	Profiling float
Markets	**	**	**	*	**	*


WOODS HOLE
OCEANOGRAPHIC
INSTITUTION
Café Thorium